



Energy Output Estimation for a Small Wind Turbine Positioned on a Rooftop in the Urban Environment with and without a Duct

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Energy Output Estimation for a Small Wind Turbine Positioned on a Rooftop in the Urban Environment with and without a Duct

Risø-R-Report

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Risø-R-1669(EN)
May 2011

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Abstract (max. 2000 char.):

Nowadays, wind turbines in general, but also urban wind turbines attained acceptance to a certain extend. Conceptual designs and some examples in reality exist, where small-scale wind turbines have been implemented close to buildings or even integrated in the building structure.

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This work is aiming to estimate how much energy a wind turbine could produce in the built environment, depending on its integration and configuration. On the basis of measurements taken on the rooftop of H.C. Ørsted Institut in Copenhagen, which is located in an urban area, a comparison of fictive free standing turbines with ducted turbines of the same type was carried out. First, a prevailing wind energy direction was detected with rough mean velocity and frequency calculations. Next, a duct was aligned with the direction, where the highest energy potential was found. Further calculations were conducted with more detailed wind velocity distributions, depending on the wind direction sectors. The duct's wind velocity amplification capability was set to 14%, while a total opening angle of 30° was assumed to be accessible from both sides.

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With the simplifying assumptions and the uncertainties at the location of measurement, the free standing turbines had an energy potential of 300kWh/m²/a for the horizontal axis wind turbine (HAWT) and for the vertical axis wind turbine (VAWT) 180kWh/m²/a. For the ducted turbines an energy output of 180kWh/m²/a was found for the HAWT configuration, while the VAWT configuration reached an output of 110kWh/m²/a. The available wind had an energy potential of 730kWh/m²/a. Evaluating these results it seems as a free standing turbine is preferable, when only considering the power output, whereas the ducted version comprises properties, which are important considering the requirements needed in the inhabited area such as safety and noise issues.

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Symbol	Explanation	[Unit]
A_{ref}	reference cross sectional area	[m ²]
$A_{turbine}$	rotor cross sectional area	[m ²]
c	scale parameter	[-]
C_P	power coefficient	[-]
C_{Educt}	ducted turbine energy coefficient	[-]
$C_{Educt,directed}$	ducted turbine energy coefficient, only duct directions	[-]
C_{Efree}	turbine without duct energy coefficient	[-]
C_{vx}	velocity at y divided by undisturbed velocity at same height	[-]
d	lifting height	[m]
d'	lifting height coefficient	[-]
$E_{turbine}$	energy harvested by turbine without duct	[Wh]
$E_{turbine,ducted}$	energy harvested by turbine positioned in duct	[Wh]
E_{wind}	energy contained in the wind	[Wh]
$E_{wind,ducted}$	energy contained in amplified wind, only duct directions	[Wh]
f	probability density function	[%]
F	fraction of time exceeding hourly mean in wind speed v_{wind}	[%]
H	mean building height	[m]
i	wind velocity indices; $v_{wind}=1\text{m/s}$ equal $i=1$	[-]
j	wind direction indices; section 1-36	[-]
k	shape parameter	[-]
$P_{turbine}$	turbines power output	[W]
P_{wind}	power contained in the wind	[W]
$prob$	probability	[%]
$U(z)$	undisturbed wind at height z	[m/s]
U_H	undisturbed wind at averaged buildings height	[m/s]
v_{mean}	mean wind velocity	[m/s]
v_{mean_amp}	mean wind velocity amplified by duct effect	[m/s]
v_{wind}	wind velocity	[m/s]
v_{wind_amp}	wind velocity amplified by duct effect	[m/s]
y	slot coordinate starting at roof gable going to wing	[m]
z	height	[m]
ρ	medium density	[kg/m ³]

1 Introduction

At the moment, knowledge about small wind turbines erected in inhabited areas is limited. At the same time private people and smaller companies are coming up with the urge of making a difference. A frequently uttered wish for local and/or private energy production with a machine in a moderate size motivated this work. In the recent years, several investigations were conducted, including field trials with existing wind turbine designs [^{1,2}], various CFD simulations of e.g. flow around obstacles and flow behavior in varied obstacle arrays [^{3,4,5}] and new rotor designs came up [^{6,7,8}]. A design, which was barely seen for a couple of decades, attracted a broad interest again, when it came to energy production in the urban environment. Due to different wind conditions, like lower average wind speed and higher turbulence intensity with increasing roughness length [⁹], compared to the wind on- and off-shore a vertical axis wind turbine might be preferable. In constant wind conditions, the HAWT concept usually performs more efficient than the VAWT concept [¹⁰]. But since the wind directions are frequently changing in cities, the HAWT loses in efficiency, since it has to adjust to the wind direction in order to operate as good as possible.

In the following, energy production estimations are conducted for a horizontal axis wind turbine (HAWT) and a vertical axis wind turbine (VAWT), exposed to a wind climate, which was found on a rooftop in an urban environment. Because a contracted duct has the ability to amplify wind velocities and wind velocities in cities usually are lower, than on the open land, rough estimations are also made for ducted wind turbines.

In general, to estimate the energy yield of a turbine several issues must be clarified.

Turbine

- Geometrical size, configuration and aerodynamic characteristics of the wind turbine (power curve)
- Wind velocity amplification characteristics, in case of a ducted turbine

Macro wind climate

- Surrounding neighbourhood
- Location of the house within the neighbourhood

Micro wind climate

- Orientation of the building
- Shape of the building
- Wind turbine position at the house
- Shape, position and orientation of the duct

Generator and control

Measurements at the location where the turbine is meant to be positioned will clarify the macro and micro climate.

2 Turbine

The swept area for a wind turbine is the projected rotor area seen by the wind. For a horizontal axis turbine the area will have the shape of a circle, and for a vertical axis turbine, where more degrees of freedom exist compared to horizontal axis turbines, the shape will depend on the shape of the rotor. The kinetic energy of the mass flow passing this area will be converted into mechanical energy at the rotor so the air flow will decelerate. The air flow experiences the spinning turbine as an obstacle, or as a resistance. The more the wind is decelerated, the more energy can be extracted until a certain point. After this the resistance increases further until the wake starts to separate and flow against the wind direction and no energy can be extracted. In between no deceleration and severe deceleration lies an optimum which was found by Betz [11]. It results in an ideal maximum power coefficient of 16/27. The power coefficient is defined as the ratio between power extracted at the rotor and power available in the wind flowing through an area of the size of the swept area. This dimensionless number helps to compare the efficiency of different wind turbines. Since the power performance of a turbine is defined as [12]

$$P_{turbine}(v_{wind}) = \frac{1}{2} \rho v_{wind}^3 A_{turbine} C_P(v_{wind}), \quad (1)$$

the instant power production is depending on the projected area, $A_{turbine}$, available wind velocity, v_{wind} , and performance properties of the turbine, depending on the current wind velocity, $C_P(v_{wind})$. The air density, carrying the kinetic energy, is $\rho = 1.225 \text{ kg/m}^3$ at a temperature of 15°C .

The power coefficient for a wind turbine differs depending on the design of each blade section (the profiles), the blade design, the regulation concept, size and tip speed ratio, which is the ratio between the tip speed and the wind speed. $C_P = 0.35$ states the approximate maximum for a small, free standing, lift driven vertical axis wind turbine (VAWT). Experiments within the development of Turby [13], reached with a VAWT (*radius*=0.3m and *height*=0.9m) maximum power coefficients of 0.21. In comparison to that, large horizontal axis wind turbines (HAWT) reach values of around $C_P = 0.48$.

With turbine dimensions like in Fig. 1 the swept area is then

$$A_{turbine} = \text{diameter} * \text{length} = 0.8\text{m} * 2.5\text{m} = 2.0\text{m}^2 \quad (2)$$

or

$$A_{turbine} = \pi * \text{radius}^2 = \pi * (0.8\text{m})^2 \approx 2.0\text{m}^2.$$

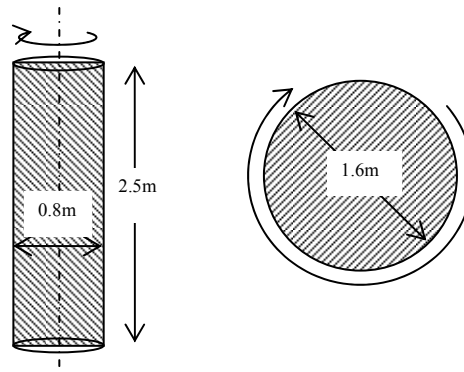


Fig. 1: Projected VAWT and HAWT area, seen by the wind

It should be noted, that most “cut-in wind speeds” for turbines are at 3 or 4 m/s. Cut-in means the moment where the generator starts to generate energy.

3 Macro Wind Climate

There exist models to predict the average wind profile in a free field (see Fig. 2). In cities, on the contrary, the models are much more complex, due to individual obstacles, influencing the flow pattern.

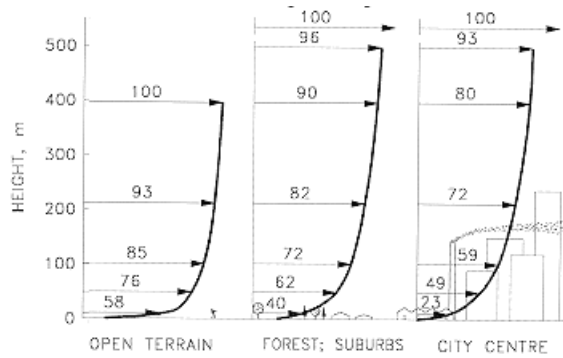


Fig. 2: Boundary layer profiles, depending on the surface roughness, z_0 [14]

3.1 Surrounding Neighbourhood

In general, cities show a similar behaviour like forests where the wind profile is lifted (see Fig. 3). Depending on the average building height, the orientation of the buildings to each other, the rooftop layout, street canyons, trees, cars passing by, to mention the most significant ones, the shape of the profile and lifting height differ. Watson et al. [15] gained a lifting height coefficient, d' , between 0.35 and 0.55, comparing a variety of conditions. d' is here the lifting height over average building height ratio (d/H).

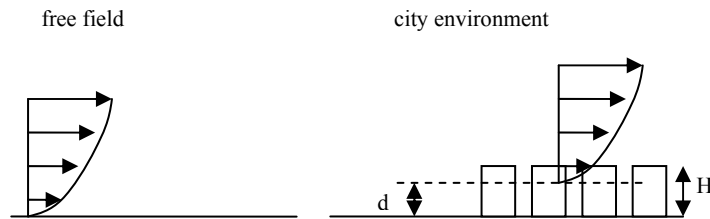


Fig. 3: Boundary Layer (BL) on a free field and lifted BL in a built area

In Fig. 4 the normalised urban wind profile is plotted, while the three lines represent the results of different theoretical approaches. The logarithmic one shows d' at $U(z)/U_H=0$. It means that at that height, around 0.55 buildings height, the wind speed will be zero. The higher above this level, the higher the wind velocity gets.

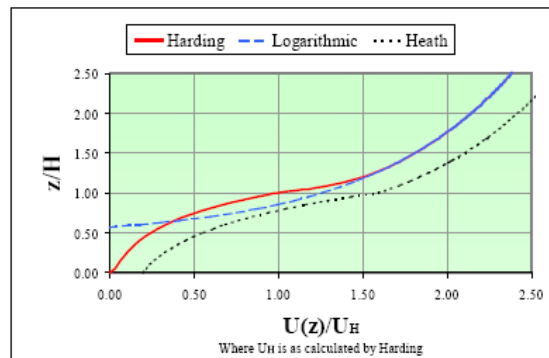


Fig. 4: Normalised Urban Wind Profile [15]

In the graph z constitutes the height above ground level, H is the mean building height, U_H is the wind velocity at the height H calculated by Harding [15], while $U(z)$ is the wind velocity at the height z . This means $z/H=1$ is at the height of the roof gable.

If a building is surrounded by higher buildings, its rooftop probably lies below the lifting height and will with that not been exposed to the city wind profile at all. Furthermore some conditions, like parks, big streets, influence the local macro flow-patterns.

3.2 Location of the House

Watson et al.'s research [15] is based on Heath et al.'s work [3]. In Fig. 5, left, the wind condition in a neighbourhood with buildings of the same height, orientated with the facade towards the wind direction is visualised with the help of simulations using Computational Fluid Dynamics (CFD). It can be seen, that the buildings in the front are exposed to higher winds than the houses positioned in the lee of the array. The picture in the middle shows the wind field above a building. It is obvious, that the wind profile is lifted. On the contrary, the building seen in the right picture is exposed to the wind profile, approaching from an open field and with that not lifted. High velocities are found at roof height. They are even enhanced at the rooftop ($velocity/U_0 > 1$).

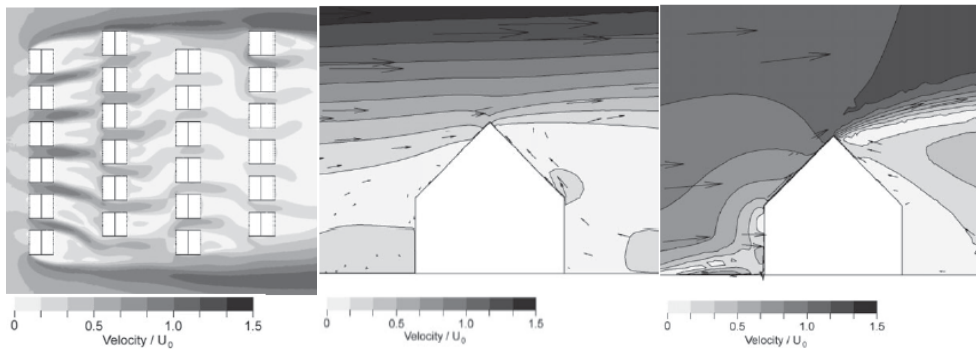


Fig. 5: Left: one of the buildings arrays; middle: house located in the “last” row; right, isolated house, no neighbours; all three pictures: wind comes from west and plotted is the ratio of actual wind velocity and wind velocity of the undisturbed wind profile [3].

4 Micro Wind Climate

By determining the appropriate wind profile, due to the neighbourhood, the flow approaching the building is known. The next step is to figure out the behaviour of the flow around the single building. However, there exist no general methods of predicting the micro wind climate, but using advanced flow simulations rather precise predictions can be established. In the following some of the most important parameters influencing the micro wind climate will be described.

4.1 Orientation of the Building

Depending on the wind direction, the flow pattern around the building will be different. One side might be sharper edged than another or one side will be exposed to the direction, where the wind blows more often.

4.2 Shape of the Building

How the velocity distribution around the building will be for a certain approaching wind velocity from a certain direction has to be figured out. The investigation of the “Aeolian Roof” [4] considered in the 2D CFD simulation an isolated house simplified as a half cylinder (see Fig. 6). They analysed the potential of an additional wing structure above the rooftop. With that a duct is formed, bearing the capability to accelerate the approaching wind.

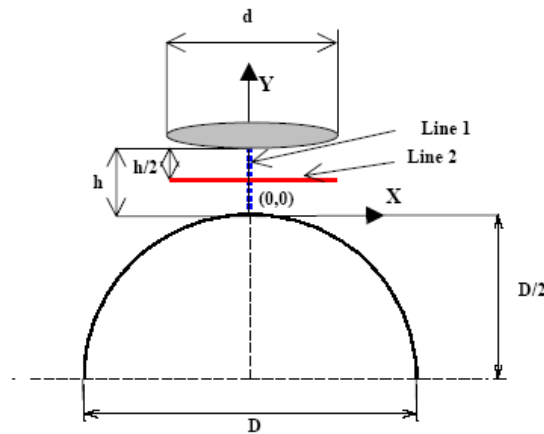


Fig. 6: Computational model with a concentrating wing above the rooftop [4]

The slot between the “wing” and the rooftop is 1m. In Fig. 7 the velocity distribution above the rooftop along line 1 is plotted for the case of an attached wing and the case without a wing.

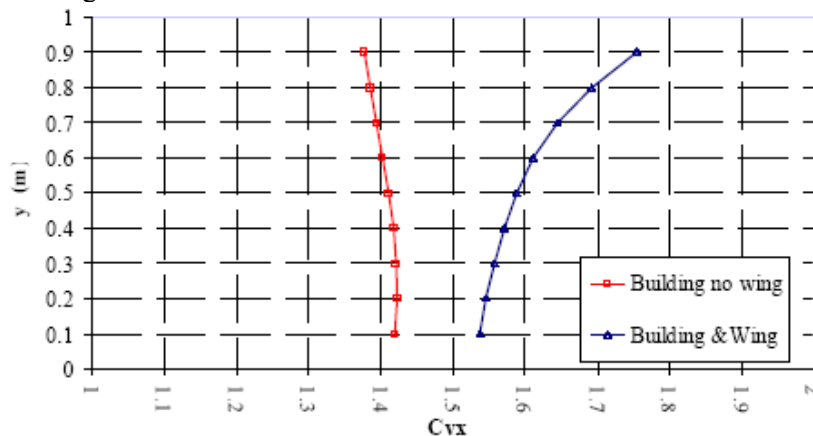


Fig. 7: Velocity amplification along line 1, with and without wing [4]

C_{yx} is the velocity at y divided by the undisturbed wind velocity at the same height of the slot. y is the coordinate with $y=0\text{m}$ at the rooftop and $y=1\text{m}$ at the end of the slot. It says that the buildings shape enhances the undisturbed wind velocity over the slot height by approximately 40 percent without the additional duct effect.

4.3 Wind Turbine Orientation

If the wind turbine is not free to adjust to changing wind directions, it will produce less energy if the wind comes from another direction, than the direction it is designed for. This fact must be taken into account in the energy production estimation.

5 Example

On the rooftop of the H.C. Ørsted Institut building, situated at Nørre Allé close to the very centre of Copenhagen, measurement devices are installed. With its location in the urban environment (see Fig. 8) and the fact, that the data is collected on the rooftop, the measurement data is applicable for a case study.

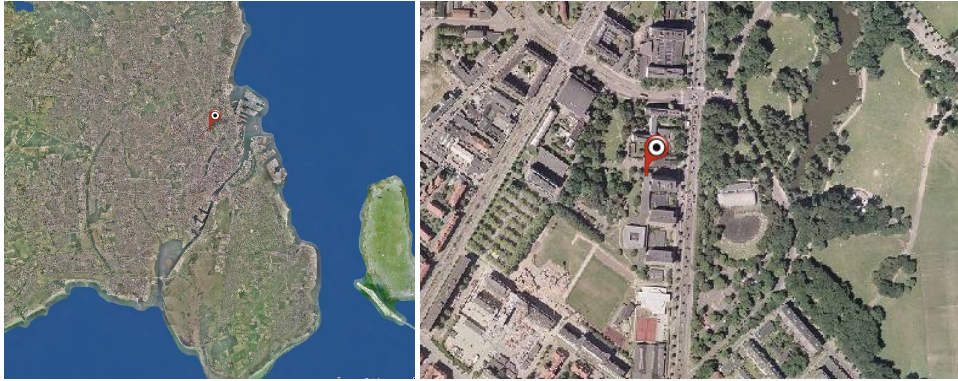


Fig. 8: Location of the H. C. Ørsted Institute in Copenhagen [¹⁶]

5.1 Wind Data

Hourly averaged data is published on the internet [¹⁷] where e.g. wind direction and wind velocity were collected in the period between March 2008 and September 2008. However, the data is not quality controlled. Furthermore it must be mentioned, that the data of a whole year needs to be analysed, in order to include the seasonal variations. The measurements are taken on the institute building, which lies furthest towards south. Fig. 9 shows the building's rooftop. Where the triangle can be seen a mast is located. A sonic anemometer on a boom is attached to the mast at a height of 8m. This figure and more detailed information about the measurements can be found in a report [¹⁸].

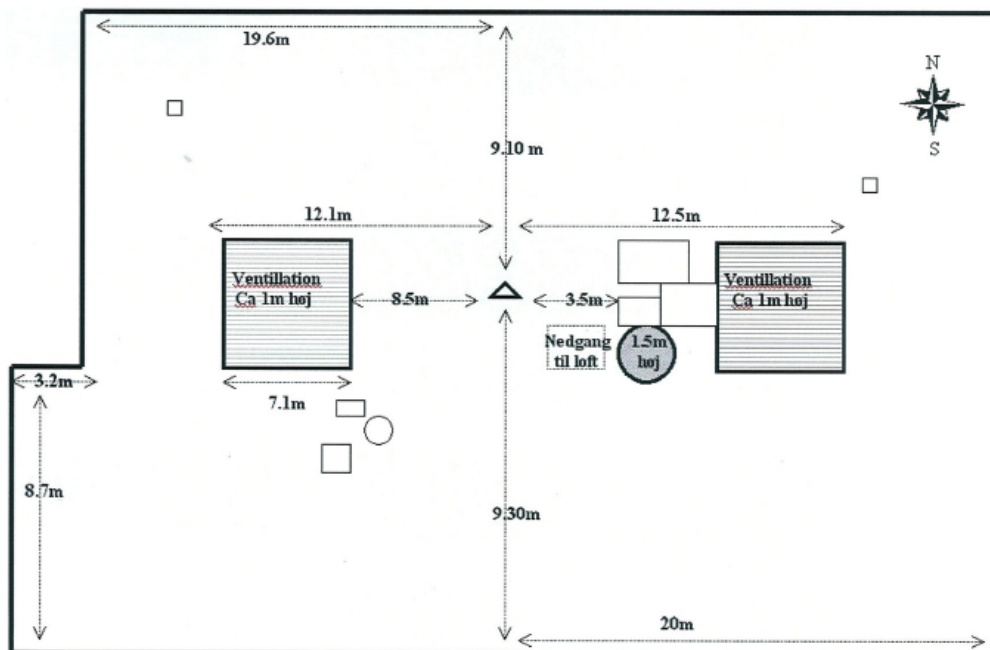


Fig. 9: Sketch of the H. C. Ørsted Institut rooftop [¹⁸].

5.1.1 Weibull Distribution

Since the wind is not blowing with the same strength all the time and the power is proportional to the cube of the wind velocity, it is helpful to determine a wind velocity distribution for wind energy exploration sites. Depending on sites the wind distribution differs. A common approach is the definition by the so called Weibull distribution

$$F(v_{wind}) = \exp\left[-\left(\frac{v_{wind}}{c}\right)^k\right]. \quad (3)$$

$F(v_{wind})$ is the fraction of time for which the hourly mean wind speed exceeds v_{wind} . It is characterized by two parameters, a scale parameter, c , and a shape parameter, k . Based on on-site measurements and the probability density function, $f(v_{wind})$, the parameters c and k can be derived (see Fig. 10).

$$f(v_{wind}) = k \frac{v_{wind}^{k-1}}{c^k} \exp\left[-\left(\frac{v_{wind}}{c}\right)^k\right] \quad (4)$$

A special case of the Weibull distribution is the Rayleigh distribution, with $k=2$, which is a typical value for many locations. A higher value of k , such as 2.5 or 3, indicates a site where the variation of hourly mean wind speed about the annual mean is small. A lower value of k indicates greater variability about the mean wind speeds.

Based on the measured data best fit is obtained by setting the two parameters to $k=2$ and $c=4.3\text{m/s}$. This Weibull distribution is representing the wind velocities at the site, not taking into account where the wind comes from. In comparison, at the Kastrup Airport, DK, the Weibull parameters at 10m height are $k=2.32$ and $c=7.1\text{m/s}$.

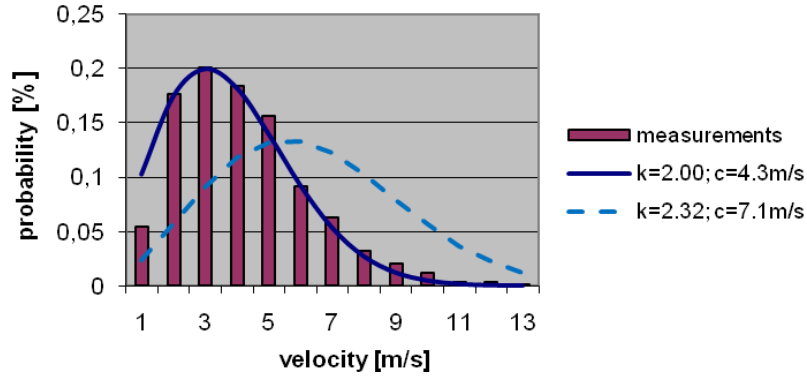


Fig. 10: Probability density function and measured wind data

5.1.2 Probability of Wind Direction

In case of a turbine not free to yaw, the knowledge about the prevailing wind direction is essential. Based on the wind data a rose is created (see Fig. 11). The percentages of the wind directions, $prob(j)$, are plotted, while it does not say anything about the velocities and their frequencies in the single sections. It has to be kept in mind that the data represents only a part of the year. Seasonal variations could change the pattern significantly.

The rose determines a prevailing wind direction ranging from south over south west to west. What this rose does not show is the mean velocities connected to the wind directions. It is important to know how much power is available from which direction, in order to find the most promising orientation.

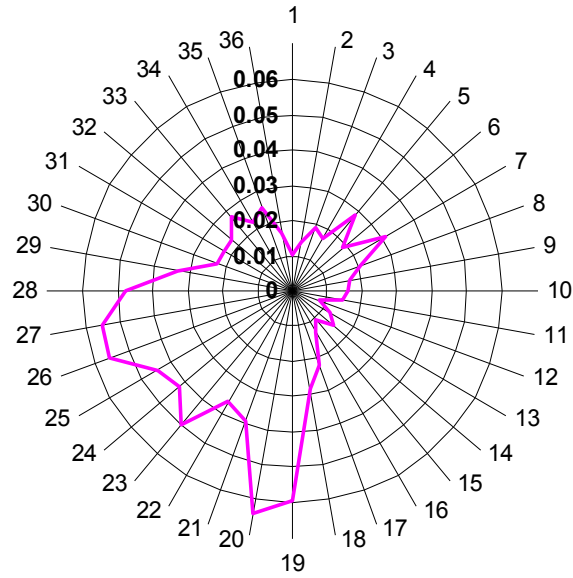


Fig. 11: Wind direction frequency rose [%]. The numbers in the periphery denotes the different sections, which equals the wind direction $\theta/10$.

5.1.3 Power in the Wind

Power delivered by the wind is generally calculated as

$$P_{wind}(v_{wind}) = \frac{1}{2} \rho v_{wind}^3 A_{ref}, \quad (5)$$

while A_{ref} is usually the swept rotor area. To keep it general the reference area for the plotted results in Fig. 12 is chosen to be 1m^2 . As an initial guess, the mean wind velocities found for the single sectors, $v_{mean,j}$, are set to the wind velocity, v_{wind} .

$$P_{wind,j}(v_{mean,j}) = \frac{1}{2} \rho v_{mean,j}^3 A_{ref} \quad (6)$$

With that an orientation towards west is preferable. The more accurate way is to apply the Weibull distribution of each single sector, instead of using the mean velocities.

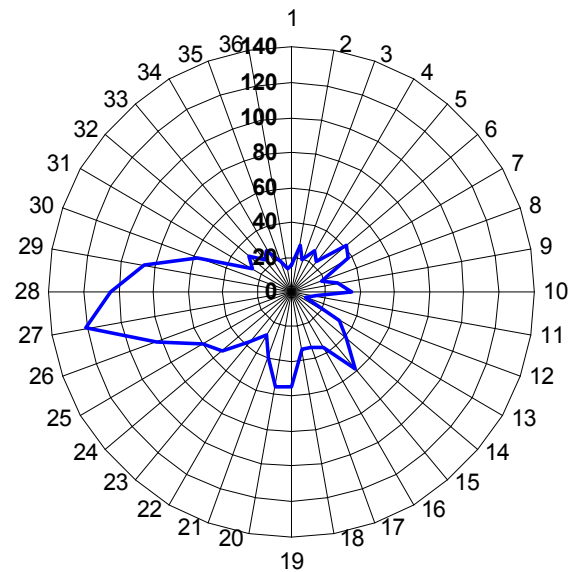


Fig. 12: Wind power rose [W/m^2]. The numbers in the periphery denotes the different sections, which equals the wind direction $\theta/10$.

5.1.4 Wind Energy Potential I

To calculate the energy potential, E_{wind} , the power in the wind has to be combined with the probability for each section, $prob(j)$. For a rough estimate, only the mean velocities of the single sections are considered.

$$\frac{E_{wind,j}(v_{mean,j})}{year} = P_{wind,j}(v_{mean,j})24h365dprob(j). \quad (7)$$

By multiplying the wind power with the number of hours in a year the wind energy potential can be plotted as in Fig. 13.

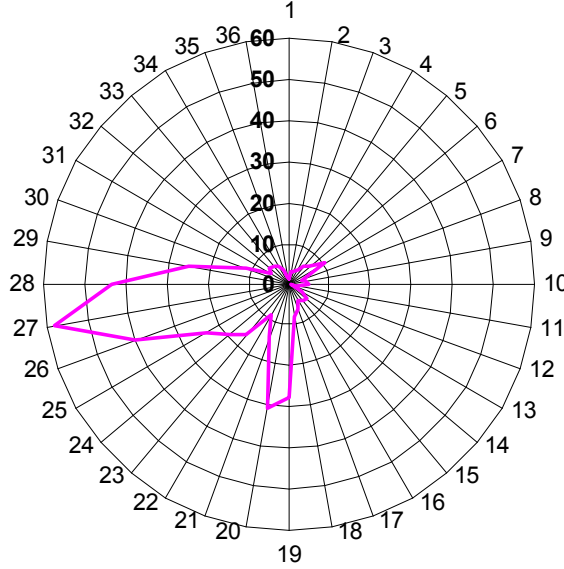


Fig. 13: Wind energy potential I [kWh/m²/a]. The numbers in the periphery denotes the different sections, which equals the wind direction $\theta/10$.

The preferred direction (section $j=26$; 27 and 28, corresponding to 260, 270 and 280 degrees) gets even more pronounced. It is also seen that a second direction almost perpendicular to section 27 contributes considerably. Considering all directions, an energy potential of 430kWh/m²/a can be calculated with the mean velocities. Summing up the energy potential of section 26-28 (140kWh/m²) and 8-10 (10kWh/m²), leads to a total of 150kWh/m² per year. How much a turbine can get out of it is a question of the turbines performance and the duct amplification quality.

5.2 Wind Velocity Enhancement by Ducts

By integrating a turbine in a duct structure, the turbine is exposed to only a certain range of directions. With on-site measurements the most promising orientation can be figured out. On the other hand such a structure can enhance the wind velocities. Several investigations in this field were done, e.g. [19], [20] and [4].

5.2.1 Aeolian Roof

Since the analysed wind data was collected on a rooftop the most appropriated work to be considered here is the Aeolian Roof investigation by Agulio A et al. [4] as describe in Section 4.2. They simulated a two-dimensional flow over a simplified building with and without a wing above the cylindrical rooftop. The wing was positioned in such a way, that it formed a 1 m high slot with the rooftop. This slot concentrated and enhanced the flow. The wind velocity averaged over the slot height showed an amplification of 14% compared to the wind velocity without the wing. In the following an amplification of 14% for the ducted case is used for all velocities and the drag effect of the turbine in the duct is neglected. That means it is assumed, that the ducted turbine performs like a free standing turbine, but produces more energy at lower wind speed.

5.2.2 Wind Energy Potential II

Assuming a slot orientated towards the direction of section 27 means that the wind velocities from section $j=26$ to section $j=28$ and $j=8$ to $j=10$ will be amplified by 14%, while the other directions cannot be taken into account. With this advantage and disadvantage an energy potential of $230 \text{ kWh/m}^2/\text{a}$ is calculated with

$$\frac{E_{\text{wind,ducted}}}{\text{year}} = \sum_{j=26}^{28} \frac{E_{\text{wind,ducted},j}}{\text{year}} + \sum_{j=8}^{10} \frac{E_{\text{wind,ducted},j}}{\text{year}}, \quad (8)$$

while
$$\frac{E_{\text{wind,ducted},j}}{\text{year}} = P_{\text{wind},j} (v_{\text{mean_amp},j})^{24h365dprob(j)} \quad (9)$$

and
$$v_{\text{mean_amp},j} = 1.14 v_{\text{mean},j}. \quad (10)$$

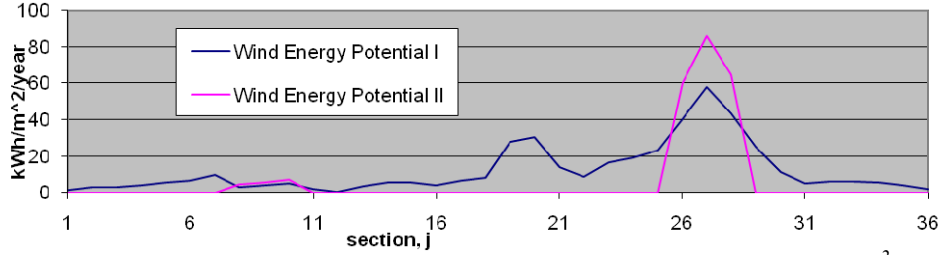


Fig. 14: Wind energy potential II, derived with mean velocity values [$\text{kWh/m}^2/\text{a}$]

It should be emphasized that it is not possible to extract all the energy contained in the wind. Thus, the wind turbine performance should be taken into account as described in the following section.

5.3 Turbine Performance

Analytical performance data for a three bladed small-scale VAWT were published by van Bussel G J W [21]. Orientated on these performance values and assuming the turbine experiencing the H.C. Ørsted Institut on-site wind conditions amplified by an Aeolian Roof duct an energy output can be estimated. To compare the performance of a VAWT with a HAWT under the same conditions, a performance curve orientated on the three bladed so called T. Urban is used. It is assumed that the ducted HAWT is performing irrespectively the inflow direction. Usually a fixed HAWT is only performing, with the wind entering the duct from one direction. The swept area of the Turby is 5.3 m^2 (VAWT) while the swept area of the T.Urban is 4.2 m^2 (HAWT).

5.3.1 Section Probability Density

For a first estimation of the energy potential the wind speed probabilities in the single sections were not considered, but derived by the mean values. This rather rough method was appropriate to determine the direction to orientate the duct. The solution should be more detailed for a turbine energy prediction, because the power output is strongly depending on the wind velocity. In the next chapter the turbine power curve will be explained. Fig. 15 shows the wind distribution measured in the single sections and the fitting Weibull distributions.

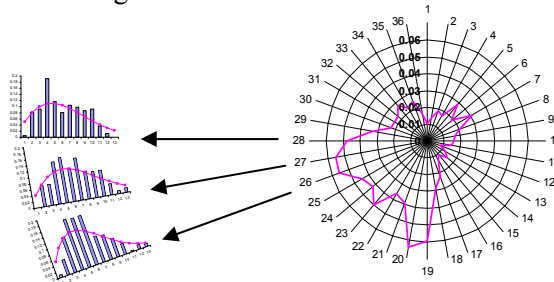


Fig. 15: Wind probability distribution for section $j=26$; 27 and 28

5.3.2 Turbine Power Curve

The power curve is the key parameter of the wind turbine energy performance. Here, we use fictive wind turbines based on data of a three bladed small-scale VAWT and a three bladed small-scale HAWT (see Fig. 16). Depending on the wind velocity the power coefficient, C_p , varies. The power coefficient is defined as the harvested power over the available power in the wind

$$C_p = \frac{P_{turbine}}{P_{wind}}. \quad (11)$$

To derive the C_p values for the ducted cases, it was interpolated between the turbines' C_p values according to a 14% enhanced wind velocity. In the figure below, two graphs are plotted for each turbine type.

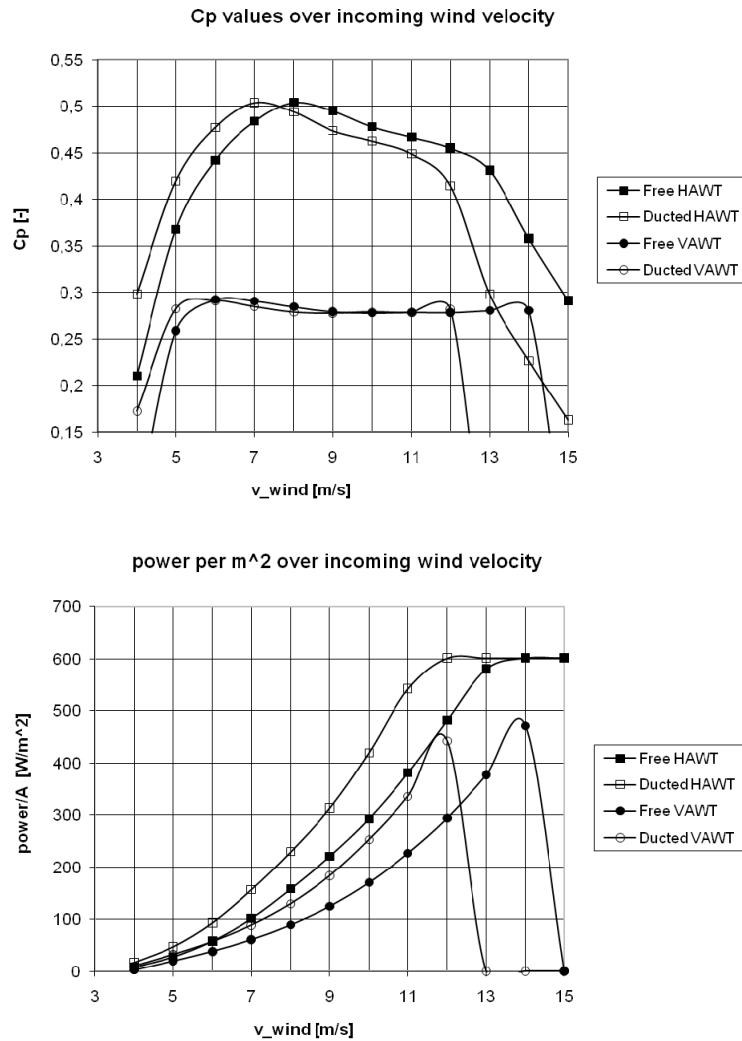


Fig. 16: Power coefficient and power per square meter curves for a HAWT and VAWT

One curve shows the turbines performance under normal conditions. The other one shows the performance under enhanced wind velocities, due to the ducting. These curves are not proven and were obtained by assuming wind velocity amplification by 14 percent over the whole velocity range. Furthermore, the C_p values are based on manufacturer graphs and are neither verified nor is the turbulence intensity influence taken into account. As well, the turbines drag effect in the duct [22] is not considered.

5.3.3 Energy Output

When the available wind is amplified by a duct, the available wind in the sections 26 to 28 and section 8 to 10 has to be multiplied with the factor 1.14 according to Aguiló et al. [4]. It has to be kept in mind that Aguiló did not investigate the enhancement factor for different wind velocities, but here all velocities are considered to be enhanced by the same value. Using the power curves, the enhanced wind velocity distribution, the probability of the wind speed from the single sections and the rotor areas gives an estimate of the turbines energy outputs. The velocity distributions found in the single sections are applied and will differ from the numbers derived by accounting only the mean velocity. Hence, the turbine energy potential for the single sections is

$$\frac{E_{turbine, ducted, j}}{year} = \sum_{i=1}^{13} \left[\frac{1}{2} \rho v_{wind_amp, i}^3 A_{turbine} C_P(v_{wind_amp, i}) prob(v_{wind, i}) \right] 24h365d prob(j) \quad (12)$$

$$\text{And in the sum } \frac{E_{turbine, ducted}}{year} = \sum_{j=26}^{28} \frac{E_{turbine, ducted, j}}{year} + \sum_{j=8}^{10} \frac{E_{turbine, ducted, j}}{year} \quad (13)$$

it is 110kWh/m²/a for the ducted VAWT example. For the ducted HAWT configuration 180kWh/m²/a is obtained. It has to be noted, that in the energy potential I and energy potential II velocities were pooled together in the manner of velocities between 0.0m/s to 1.0m/s representing 1m/s and so on. For the energy output here the more appropriate pooling of 1.5m/s to 2.4m/s representing 2m/s was applied. For the energy potential I, based on the measured velocities, the value is then about 730kWh/m²/a, and 270kWh/m²/a for energy potential II. The results are shown in Fig. 17.

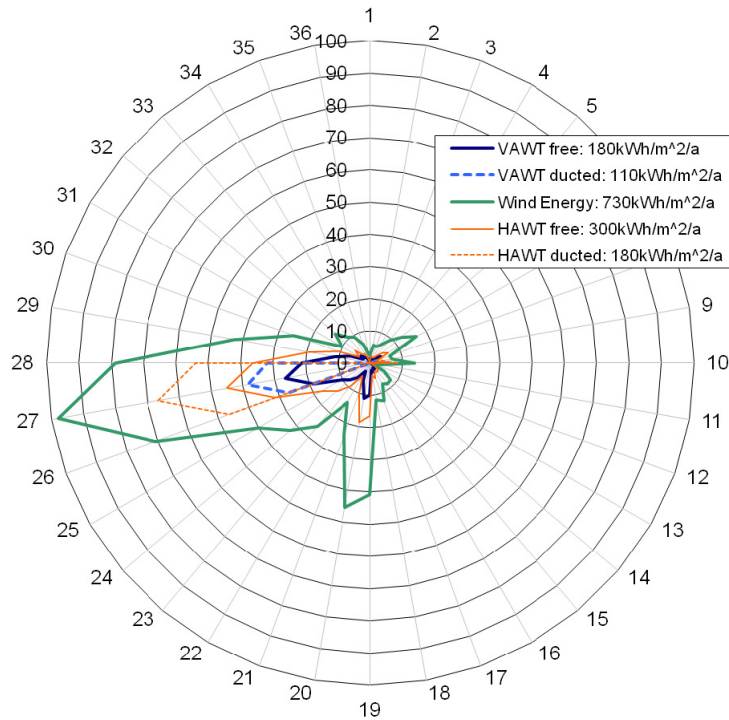


Fig. 17: Wind Energy, free standing turbines and ducted turbines energy potential, derived with the second averaging method.

Considering only the wind captured in the duct sections, the amplification causes a

$C_{Educt,directed_VAWT} = 0.39$ and $C_{Educt,directed_HAWT} = 0.67$, with the definition

$$C_{Educt,directed} = \frac{E_{turbine,ducted}}{E_{wind,ducted}}. \quad (14)$$

Seen on the whole spectra delivered by the wind the power coefficient of the ducted system is $C_{Educt_VAWT} = 0.15$ and $C_{Educt_HAWT} = 0.25$ with

$$C_{Educt} = \frac{E_{turbine,ducted}}{E_{wind}}. \quad (15)$$

The same turbines which would be free to harvest the wind from all directions, but without the amplifying effect and assuming no losses by re-aligning with changing wind directions, reach power coefficients of $C_{Efree_VAWT} = 0.25$ and $C_{Efree_HAWT} = 0.41$ with

$$C_{Efree} = \frac{E_{turbine}}{E_{wind}}. \quad (16)$$

6 Discussion

With the chosen values in this example the energy prediction for a year is 110kWh/m²/a for the ducted VAWT and 180kWh/m²/a for the free standing VAWT. For comparison the ducted HAWT reaches an output of 180kWh/m²/a and the free standing HAWT an output of 300kWh/m²/a. Assumptions which are made to derive these results are connected to several uncertainties.

- The wind data is not representative for the whole year, for all kinds of buildings and is not quality controlled
- The building shape which is connected to 14% velocity amplification is simplified and does not represent common buildings geometry
- The amplification factor of 14% is stated for only one wind velocity, but is applied to the whole wind velocity range
- For the simulation of this amplification the effect of a turbine in the slot is not considered
- The slot geometry does not represent an existing design
- The turbine power curves are based on manufacturer data
- The turbine power curves may vary for different turbulence intensities
- For HAWTs the efficiency may drop significantly in climates where the wind direction changes frequently, which is not taken in consideration here
- A direction range for the duct of only 30° is considered and skew angles effect neglected
- The ducted HAWT is considered to operate in wind entering the slot both from the one and the other direction

A significant number which was not mentioned so far is the load factor which is defined as the annual average power divided by the rated (maximum) power. Both used example turbines are rated with 2.5kW, the one at 12m/s and the other at 13m/s. Since the wind is not blowing with the rated wind velocity all the time, the load factor for large-scale turbines, depending on the site, is approximately 25%. Although the C_E values, found in this case study, seem to be promising, the load factor for the free standing turbines is about 5% and for the ducted turbines 3%. These numbers lead to the suggestion to design small-scale turbines for the urban environment for lower rated wind velocities and with cut-in wind speeds below 4m/s.

Conclusion

The result of the investigation of the energy output for ducted and traditional wind turbines on a rooftop in urban environments is that a ducted rotor bears the potential to deliver ~60% of the energy of a free standing rotor exposed to the same wind scenario. The applied scenario shows two prevailing directions in terms of wind energy potential. With that the location is not optimal for using a duct, because a significant amount of energy cannot be harvested by the ducted configuration. However, the integration in the roof cases the wind turbine, which is important concerning safety and visual impact.

To make sure that citizens are safe in case of a blade breaking, grids at the ducts inlet and outlet can be applied. However, using grids introduces further losses. In the urban environment some reductions in efficiency may be tolerated, due to more subjective aspects. Wind turbines in dense populated areas constitute a piece of architecture. With the integration in the common roof, the architecture will keep the familiar face of a building.

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